Measuring the Age of the Universe Using the Old Galactic Globular Clusters

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Abstract

This paper describes ongoing collaborative efforts between staff at the Jet Propulsion Laboratory (JPL) Table Mountain Observatory (TMO) and Students in the JPL/California Sate University Los Angeles Consortium for Undergraduate Research (CURE) to estimate the age of the Universe using distant globular clusters (GCs) in the Milky Way. Observations were made using a 0.6-m telescope at TMO. Data analysis was carried out by students in the CURE program, using resources at TMO. Archival HST data of the same objects will compliment the ground-based data. This paper concentrates on the ground-based effort to determine metalicities from Washington-DDO photometry

1. Introduction

Globular clusters (GCs) formed, with galaxies, ~ 1 Gyr after the big-bang (Chaboyer, 1995). GCs are 15-18 Gyr old (Vandeberg, 1987). Precise ages from GC luminosity functions (Padoan and Jiminez, 1997, Bergbush and vandeberg, 1997) will be used to estimate the of the age of the universe to < 1 GYr. Distances to GCs will be found, *independently of reddening and metalicity,* from the parallactic motions of their centroids; as measured from positions of the stars (>10^4) in their cores on High-resolution HST images taken ~1Year apart (Gillam, 2000) . There are ~20-40 Galaxies (I =22-25) in these images (Griffiths et Al., 1993). They will be used as non-moving reference objects. Color-Magnitude diagrams will be constructed from archival WFPC2 data already procured from STSCI. Absolute ages will be derived from luminosity functions *independently of distance* (Gillam, 2000). Star counts in adjacent sub-giant luminosity bins will be used to measure cluster ages. Distances, ages and metalicities will be separately measured and combined using stellar evolutionary and atmospheric models and to check consistency.
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2. Collaborators

This project was started in June of 1997. It has a growing list of collaborators from some the schools participating in the Consortium for Undergraduate Research (CURE). These include Cal. State Los Angeles (CSLA), Los Angeles SW College (LASC), Los Angeles City College and (LACC) See below.

Name	School	Period	Contribution
Maria Rodriguez	**LASC**	**1997 - 1998**	**Observations**
Calvin Bruton	**LASC**	**1997 - 1998**	**Observations**
Bonaventure Osuji	**LASC**	**1997 - 1998**	**Observations**
Edward Bledsoe	**LASC**	**1997 - 1998**	**Observations**
Jomel Atienza-Rosel	**CSLA**	**1998 - 1999**	**Observations**
James R. Foster	**CSLA**	**1999 - 2000**	**Observations**
Alper K. Ates	**CSLA**	**1999 - 2000**	**Observations**
Jasmine Patton	**LASC**	**1999 - 2000**	**Observations**
Charles Jordan II	**LASC**	**1999 - Now**	**Observations and data reduction**
Heath Gibson	**CSLA**	**Fall 1999**	**Observations**
Dee Asbury	**LACC**	**Spring 2000**	**Data reduction**
Janelle Rodriguez	**LACC**	**Spring 2000**	**Data reduction**
Michael Balancio	**LACC**	**Summer 2000**	**Data reduction**

3. The Program

One-hour C, M, Mould I and 51 exposures down to 20th mag (S/N ratio>100) will be made to precisely measure the sub-giants and turn-off stars for the LF age estimate and provide the precision (+/-.003 dex) needed to separate giants and dwarves with (C-M) < 1.0. Exposures will be taken when clusters are on the meridian to minimize atmospheric refraction and extinction. The 1024x1024x24μm LN2-cooled CCD camera on the TMO 0.6-m telescope provides an FOV of 8.7 x 8.7 arcmin. All the clusters in table 1 can be adequately covered with a grid of 4 overlapping fields in each filter.

Table 1. Target Globular Clusters

Name	RA	Dec	b	E(B-V)	VHb	RGc	Fe/H	Rt.	Amax
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
4147	12:08	19	+77.19	0.02	16.85	19.9	-1.80	7.244	1.037
M53*	13:10	18	+79.77	0.00	16.94	19.2	-2.04	21.878	1.042
5053*	13:14	18	+78.94	0.01	16.63	16.7	-2.17	13.804	1.042
M3	13:40	29	+78.71	0.00	15.68	12.6	-1.66	38.905	1.004
5466*	14:03	29	+73.59	0.00	16.6	16.4	-2.22	20.893	1.004
M5	15:16	02	+46.8	0.03	15.11	6.6	-1.40	28.84	1.184
M13*	16:40	37	+40.91	0.03	14.95	8.9	-1.65	26.915	1.001
M92*	17:16	43	+34.86	0.02	15.1	9.8	-2.24	16.596	1.011
M72	20:51	-13	-32.68	0.03	16.85	12.7	-1.54	8.71	1.477
M2	21:31	-1	-35.78	0.02	16.05	10.9	-1.58	16.218	1.227

Column (1) cluster name, (2) RA in hrs. and mins. , (3) Dec in degrees, (4) Galactic latitude in degrees, (5) interstellar reddening, (6) horizontal branch apparent magnitude, (7) galactocentric distance in Pc, (8) Fe/H, (9) tidal radius in arc min. and (10) minimum airmass at TMO. An asterisk indicates those considered to be the oldest (Chaboyer, 1995)

Dark-of-moon time is required each month. Approximately half the data has already been collected. Another 3 years is required to complete the data collection. A team of 2-4 CURE students is responsible for collecting the astronomical data and 2 more are involved in data reduction at any time. Targets are scheduled by Gillam, using TIMELINE.XLS

The current target is M92. The [Fe/H] measures in column (8) of Table 1 are a guide to relative cluster age. M92 is the most metal deficient (smallest Fe/H) and so it is the oldest of our target clusters. It is not a distant from the Earth (as measured by increasing VHb in col. (6) as the others in the list. This makes it a classic choice for study in-depth.

FIELD	OBS TYPE	FILTER	HOLE	EXP TIME	LST START	LST END	MIDDLE AIRMASS
M92NW	OBJECT	Mould I	D	00:10:00	16:05:42	16:15:42	1.037
M92NW	OBJECT	51	E	00:10:00	16:16:46	16:26:46	1.029
M92NW	OBJECT	51	E	00:10:00	16:27:50	16:37:50	1.023
M92NW	OBJECT	C	A	00:10:00	16:38:54	16:48:54	1.018
M92NW	OBJECT	Mould I	D	00:10:00	16:49:58	17:00:58	1.014
M92NW	OBJECT	51	E	00:10:00	17:01:02	17:11:02	1.012
M92NW	OBJECT	51	E	00:10:00	17:12:06	17:22:06	1.011
M92NW	OBJECT	C	A	00:10:00	17:23:10	17:33:10	1.012
M92NW	OBJECT	Mould I	D	00:10:00	17:34:14	17:44:14	1.014
M92NW	OBJECT	51	E	00:10:00	17:45:18	17:55:18	1.018
M92NW	OBJECT	51	E	00:10:00	17:56:22	18:06:22	1.023
M92NW	OBJECT	C	A	00:10:00	18:07:26	18:17:26	1.03
M92NW	OBJECT	Mould I	D	00:10:00	18:18:30	18:28:30	1.038
M92NW	OBJECT	51	E	00:10:00	18:29:34	18:39:34	1.048
M92NW	OBJECT	51	E	00:10:00	18:40:38	18:50:38	1.059
M92NW	OBJECT	C	A	00:10:00	18:51:42	19:01:42	1.073
M92NW	OBJECT	Mould I	D	00:10:00	19:02:46	19:12:46	1.088
M92NW	OBJECT	51	E	00:10:00	19:13:50	19:23:50	1.105
M92NW	OBJECT	51	E	00:10:00	19:24:54	19:34:54	1.124
175518	STANDARD	51	E	00:00:20	19:36:14	19:36:34	1.33
180028	STANDARD	51	E	00:00:20	19:38:34	19:38:54	1.142
186293!	STANDARD	51	E	00:00:20	19:40:49	19:41:09	1.102
186312!	STANDARD	51	E	00:00:20	19:42:53	19:43:13	1.102
192344	STANDARD	51	E	00:00:20	19:45:07	19:45:27	1.138
194598	STANDARD	51	E	00:00:20	19:47:17	19:47:37	1.117
G3	STANDARD	Mould I	D	00:05:00	19:49:37	19:54:37	1.609
G3	STANDARD	Mould I	D	00:05:00	20:07:41	20:12:41	1.508

This is part of a timeline file for 07/30/2000 UT. It shows part of a typical set of observations. Theses include the cluster (M92), and various standard star frames. Exposure times have been standardized for efficiency. The type of observation is indicated (OBJECT or STANDARD) as is the filter required and the exposure time. If the exposure is started at “LST START” and ended at “LST END” the air-mass will be that indicated in the “MIDDLE AIRMASS” column. TIMELINE.XLS computes these to minimize the cluster air-masses and to spread the standards over an evenly spaced range of air-masses. Air-mass coefficients for each night can then be calculated (Gillam, 2000). TIMELINE.XLS sorts the exposures in order of increasing starting LST and adjusts start times to allow time between exposures to move the telescope and save data to the remote disk. Seventy images may be taken in a typical night.

Timelines are made available to the observer via the TMO web site at tmo-web.jpl.nasa.gov.

4. Precision Stellar Photometry

Estimating globular cluster ages demands precision photometric measurements of very faint (V<20 mag.) stars. This is because errors tend to blur the distinctions between giants and dwarves, in both color-magnitude and color-color diagrams, for main sequence turn-off stars and sub-giants.

We are attempting to measure the flux from these stars with a precision of better than 1 part in 100 (<0.01 mag).

Standard Stars

Very precise photometry (+/- .003 mag.) of the standards is required so that they do not contribute more error to the results than the cluster star measurements. This can be achieved because a large number of observations of the standards have been made. Each standard star field contains 5 – 9 stars and each has been observed ~20 times over three years.

Their images on the CCD frame are separated by hundreds of pixels and do not overlap. Their relative magnitudes can be most efficiently measured through large apertures (compared to the FWHMs of the star profiles) if the background or sky flux is measured accurately. This phase of the project has concentrated on developing semi-automatic means, using NOAO IRAF (Tody, 1986) , to do this.

Cluster Stars

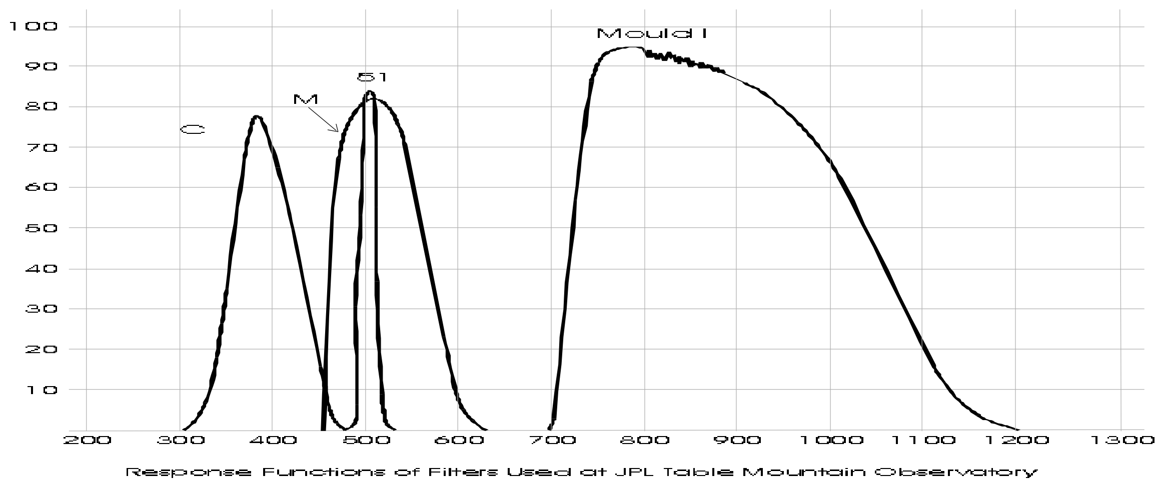
Their images are generally overlapped and blended with one or more neighbors. This is because a cluster frame contains 1500 – 2000 star images.

Under these conditions photometry relies on a prior estimate of the shape of the stellar profile and scaling and subtraction of that profile at the position of each star identified. These tasks are carried with the DAOphot package in IRAF(Stetson, 1987).

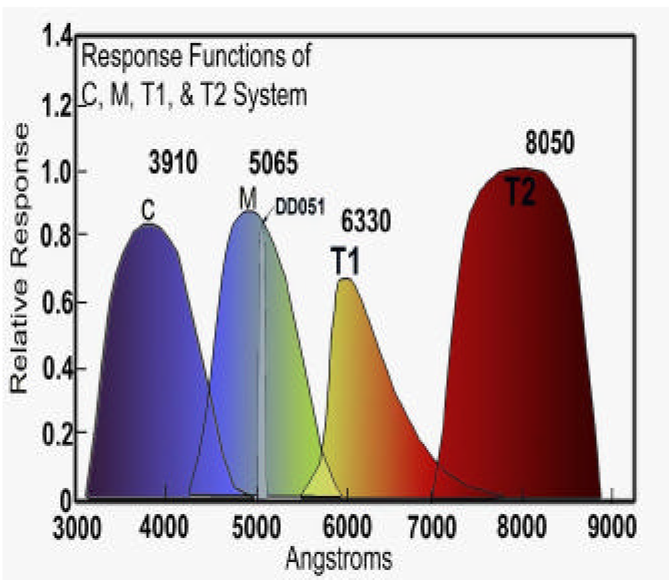
Successful DAOphot photometry requires a) symmetric star images, b) good estimation of the orientation (wrt the image x and y axes) of the star images, and c) good estimation of the shape of those images. IRAF has been used to help automate this process.

5. The TMO Washington Filter Set

The filter set used at TMO was purchased from the Omega Optical Company in a group-buy with C.T.I.O. These filters closely approximate the original design (1). The curves are reproduced from data supplied by Omega Optical. The horizontal scale is nanometers. The vertical scale is relative sensitivity.



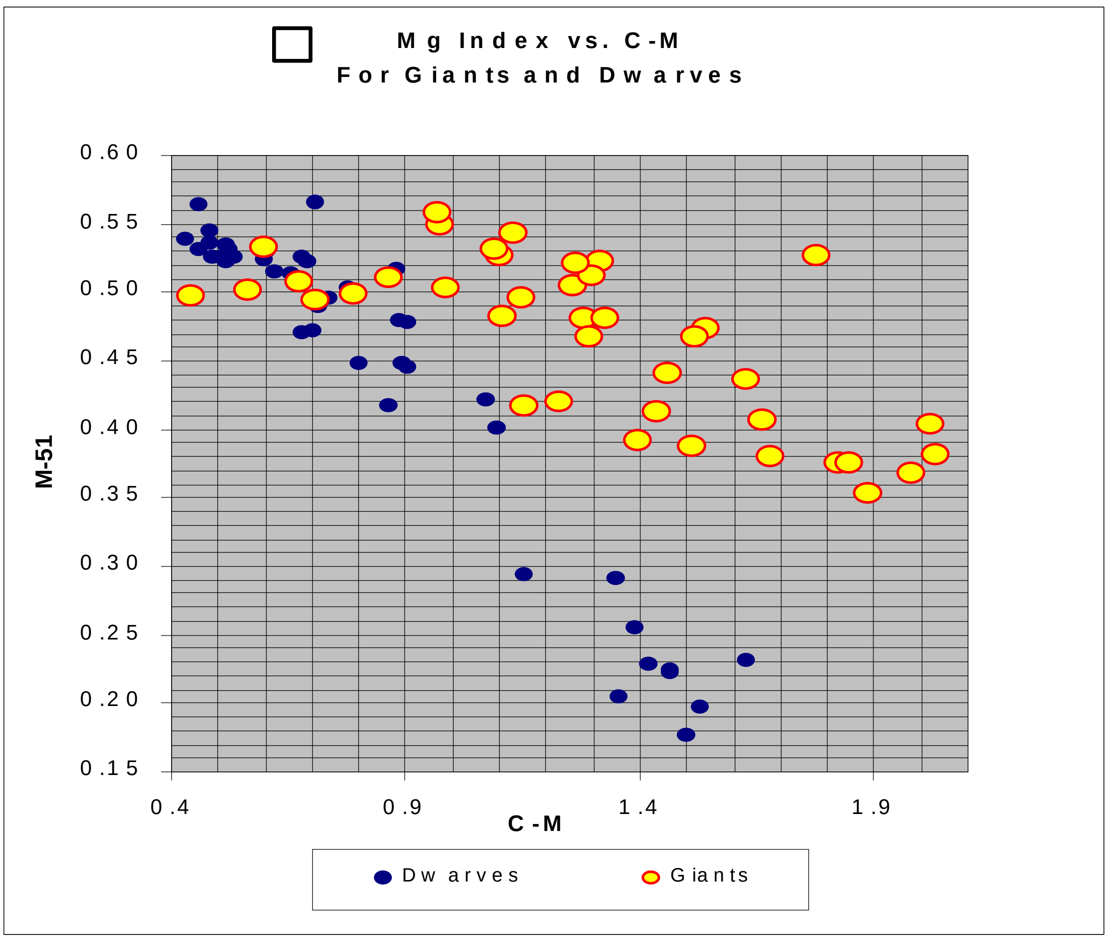
The Canterna filter set is shown below for comparison. This figure was adapted from Canterna 1976. The Mould I filter (above) is used in place of the T2 filter (below). It is simpler and cheaper than the T2 filter. The TMO set includes a T1 filter but it is not used.



The Mould I filter has considerable excess response longward of 900 nm when compared to the T2 filter. The effect this “red-leak” has on the ability of the Mould I to reproduce T2 magnitudes will be investigated.

6. The Washington-DDO Color-Color Diagram

Contamination of globular cluster giant branches by field dwarves, with the same effective temperatures and apparent magnitudes, can be removed on the basis of stellar-atmospheric Mg absorption strengths, using the “51” filter (McClure, 1976, Clark.and McClure 1979). (M-51) colors are almost unaffected by reddening because the center wavelength of the 51 and M filters are almost the same. This allows giants to be separated from dwarfs without a detailed knowledge of the reddening to each star in the field. The data on field stars plotted below (Wallerstein and Helfer, 1966, Canterna, 1976 Geisler, 1984, Geisler, 1986, Geisler et Al., 1993, McClure, 1976, Clark.and McClure 1979, Lang 1996) were de-reddened to approximate the cluster stars that are all at the same distance.



The Washington-DDO color-color diagrams of our program clusters are expected to look like this.

7. Biases, Darks and Flats

The raw images contain artifacts and biases not due to the light from the stars. A number of steps must be taken to correct for these before the data can be analyzed.

The CCD camera produces an image in the absence of light which is made up of a constant value (the bias level) in each pixel plus a component which increases with exposure time (dark current).

The telescope optics restrict the cone of light reaching the CCD chip in such a way that the center of the chip is illuminated more strongly than the edges – *even if the light source is flat.*

Cosmic ray hits (which are spatially random) and defective (hot) pixels must also be taken into account. These can be removed (as opposed to minimized) because they are known to be independent of the CCD illumination process.

The bias levels were measured from CCD frames of zero exposure time in the dark.
The dark was measured by repeating the bias process with the camera shutter open for a time similar to that of the cluster and standard star exposures.

The flat field response of the camera/telescope was measured from images of the morning or evening twilight sky.

All of these artifacts are subject to noise (random error) due to the physics of the flow of particles (photons or electrons*). This must be minimized by summing over large sets of identical frames.*

8. Programs Written for This Project

Program	Function
DATA_REVIEW.CL	Compiles image statistics for the raw data, computes airmasses and makes a copy of the raw data in the calibration directory.
MAKEBIAS.CL	Presents bias frames for selection and combines those selected into a single grand-bias.
MAKEDARK.CL	Presents dark frames for selection and combines those selected into a single dark current (counts/msec) frame.
MAKEFLAT.CL	Presents flat-field frames for selection and combines those selected into a single high-precision flat-field for the date range covered by the raw data.
VIEWFITS.CL	Performs dark subtraction, bias subtraction and flat-fielding using files produced by the MAK* programs. It also performs photometry of isolated stars.
SEARCHPSF.CL	Does crowded-field cluster photometry by repeated application of DAOphot.
MIMSTAT.CL	Produces a screen printout of the statistics for files in the calibration directory.
CMDGEN	Produces color-magnitude diagrams from DAOphot photometry files.

Several scripts were written to efficiently select images and perform the data reduction steps. All, except CMDgen, are NOAO/IRAF (Tody, 1986) “CL” scripts that take advantage of the image processing tasks available in IRAF. These run on an HPUX workstation or a SUN Microsystems Spark-Station. One is a GUI-driven visual basic for Excel program running on a laptop. All three computers are available to the collaborators at the Jet Propulsion Lab. Table Mountain Observatory.

Image arithmetic and other functions are performed on copies of the data to preserve its integrity.

The CL scripts take FITS images and convert them to IRAF format before processing them. They convert their results (usually images) back to FITS files and delete intermediate IRAF files. This is necessary to avoid filling up the data disk on the reduction computer.

The MAK*.CL programs all use the median averaging process to *reject deviant pixels* (such as cosmic ray hits) during the combination process. This is superior to a simple averaging which merely reduces the effect on the combined image of pixels with values that deviate from the characteristic value for a given input image set.

SEARCHPSF.CL is shell which runs DAOphot. Its main function is to make repeated passes through the reduced cluster images until all acceptable detections have been measured. The result of a DAOphot pass is an image with fewer stars in it than at the start because the program subtracts them from the image after measurement. This reveals the faint ones previously blended with those removed. SEARCHPSF attempts to remove stars in layers by operating on the result of the last pass. It queries the analyst for shape and image orientation information on each pass. This information is crucial to the accurate removal of stars from the image. Accurate removal leaves behind only the local sky level. This indicates that a good photometric measurement has been made. Each pass also produces a file of positions and instrumental magnitudes.

9. Data Handling Chain

The following steps were taken in gathering and processing the raw astronomical images prior to analysis.

0. Making the observations
- Observations are made according to a timeline generated by TIMELINE.XLS

1. Visual inspection of raw data
- Images displayed one-by-one using XIMTOOL.
- Images of poor quality are noted and avoided in later processing.

2. Automated inspection of raw data,
- Air-masses and image statistics calculated using DATA_REVIEW.CL.
- Uses information stored in the header of the data file.
- Air-masses are required in step 10.
- Promotes a copy of the raw file to a calibration directory with a date-tag attached to its file name.
- Produces a text file that is ingested into an MS Access database for rapid analysis.

3. Construction of a grand-bias frame
- Uses MAKEBIAS.CL
- Uses date-tagged bias files in the calibration directory
- Places resulting grand-bias in the calibration directory.

4. Construction of a super-dark frame
- Uses MAKEDARK.CL
- Uses date-tagged dark frames and biases files in the calibration directory
- Places resulting super-dark in the calibration directory.

5. Construction of a high-precision flat-field frame
- Uses MAKEFLAT.CL
- Uses date-tagged flats, darks and biases files in the calibration directory

- Places resulting high-precision flat in the calibration directory.

6. Reduction of standard star field images
7. Reduction of cluster images,

8. Isolated star photometry (standards)

- Uses VIEWFITS.CL
- Results placed in a “reduced” directory.
- Writes photometry and quality comments to a text file for use in an Access data base.

9. DAOphot (crowded field) photometry

- Uses SEARCHPSF.CL

10. Correction of all data for air-mass,

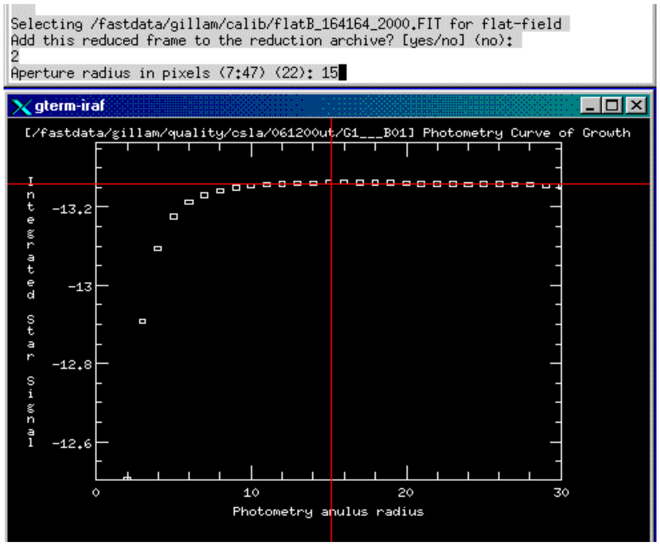
11. Transformation of standard star instrumental magnitudes to the standard system.

- Uses Access databases.

12. Transformation of cluster photometry to the standard system
13. Combination of C and M filter photometry lists to produce the (C-M) colors of the cluster stars,
14. Combination of the M and 51 lists to produce (M-51) colors for the cluster stars,
15. Combination of the (C-M) and (M-51) lists into a color-color array.

Steps 1 – 5 must be performed in the order above because every CCD image includes bias and dark contributions.
Steps 12 – 15 were performed by CMDgen.xls

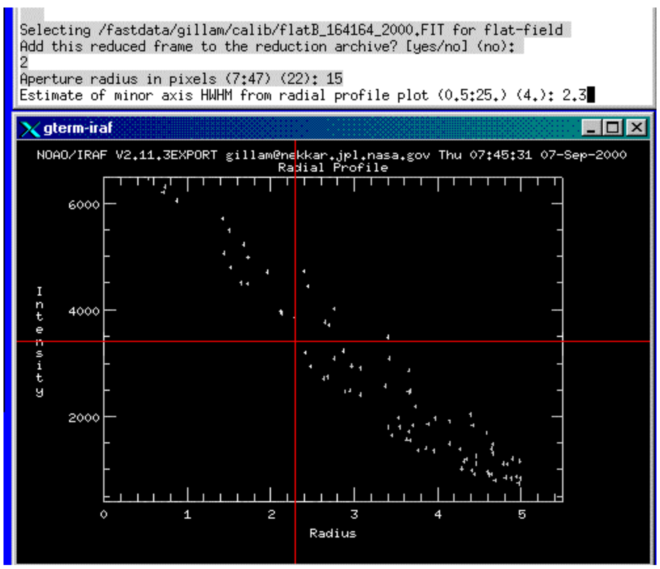
10. VIEWFITS.CL



The first panel shows the curve of growth method for estimating the total brightness (counts) of the star.

Each point represents the counts inside concentric boxes centered on the star position after the sky counts have been subtracted from each pixel.

After the "edge" of the star is reached the total counts are constant. This value is entered as the photometry aperture radius on the VIEWFITS command line.

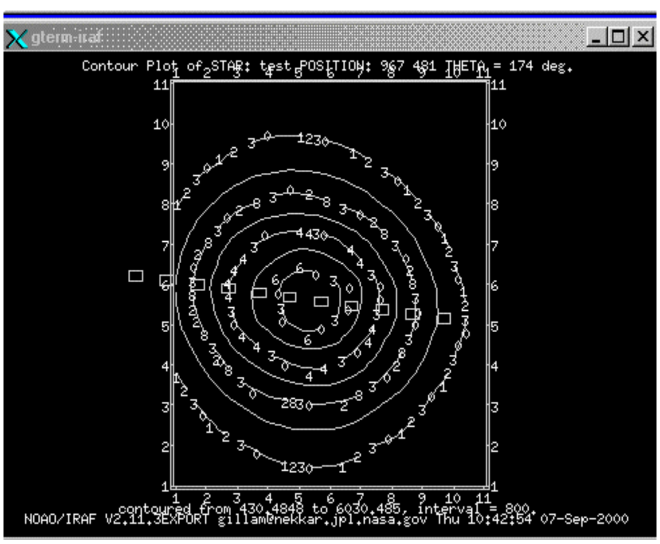


The second panel is a plot of the intensity (counts) vs. distance from the star center.

The inner edge of the envelope is due to points along the minor axis of the star image and the outer edge is from points along the major axis.

The minor/major axis ratio can of the star image is estimated by measuring the envelope at a fixed intensity. We use half the peak intensity.

This ratio is required by DAOPhot.



This is an intensity contour plot with a line superimposed on it. The line is rotated from the VIEWFITS command line until it is coincident with the major axis of the plot.

This measures the position angle of the image wrt. the image axes. DAOphot requires this parameter.

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